Present HWI Landscape: NPDGamma, n-3He, n-4He Spin Rotation

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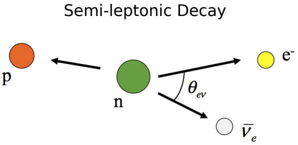
UNIVERSITY of VIRGINIA

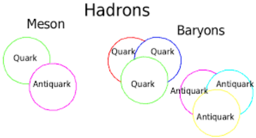
OAK RIDGE National Laboratory

Hadronic Weak Interaction: First hints at QCD

Generally, weak interactions can be categorized into three systems:

- leptonic: c.f. muon decays, only fundamental particles
- semi-leptonic: c.f. neutron decay, etc. The underlying interactions are understood, but many experimental efforts ongoing for more precision
- Hadronic (composite particles with 2 or more quarks): contains internal structure of the nucleon, and at low energy, **non-perturbative strong QCD**





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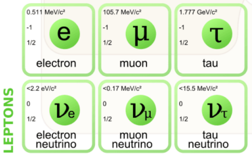
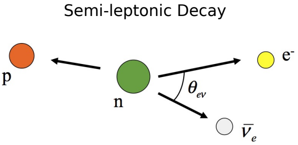
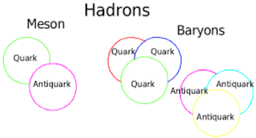


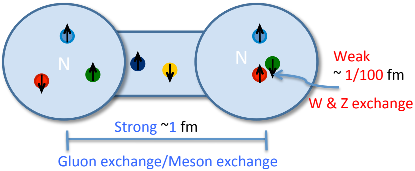


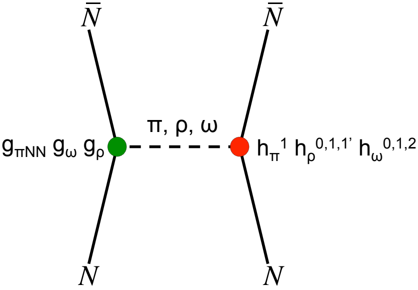


HWI: still trying to understand the underlying physics!

If the strong + weak (pert) is unable to explain these effects, then there could be some non-trivial QCD dynamics

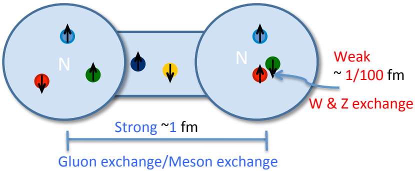
Hadronic Weak Interaction: Connections to QCD

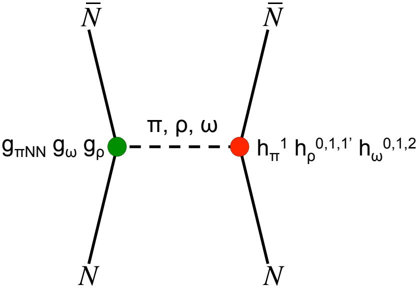




relative scale $\sim m_\pi / m_W \sim 10^{-7}$

- The range for W and Z exchange between quarks (10^{-2}fm) is small compared to the nucleon size (1fm) $\rightarrow$ **HWI is first order sensitive to short range quark-quark correlations in hadrons!**





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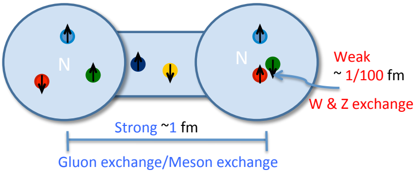

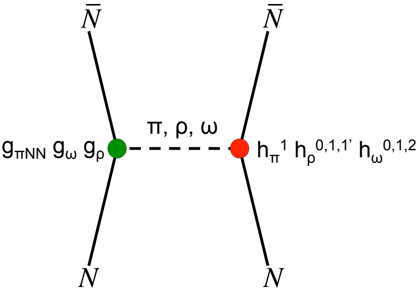

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- Ratio of weak to strong amplitudes is 10^{-7} $\rightarrow$ Use Parity Violation

Hadronic Weak Interaction: Connections to QCD

Although we understand the theoretical framework of the quark-quark weak interaction, **low energy interactions between nucleons contain both the strong and weak interaction.**

- quark confinement, non-perturbative nature of QCD
- low energy nucleon-nucleon interactions cannot be calculated analytically

$\rightarrow$ try to use the weak interaction PV to expose QCD!

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$\rightarrow$ try to use the weak interaction PV to expose QCD!

Luckily, the range of the strong interaction is long compared to the size of the nucleon at low energies and the direct exchange of the W and Z bosons is suppressed. This fact lends the nucleons to be treated as bound states.

- This led to the first Meson Exchange Theories in the 1980s
- EFT 2000s
- $1/N_c$ expansions in 2010s

Hadronic Weak Interaction: Theory Overview

An Overview:

- DDH meson exchange model: PV potential π, ρ, and ω with strong and weak vertex. 7 Weak couplings h_{π}^{1}, $h_{\rho}^{0,1,2}$, $h_{\rho}^{1\prime}$, and $h_{\omega}^{0,1}$
  - B. Desplanques, J. F. Donoghue, and B. R. Holstein, Annals of Physics, 124 (1980)
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- EFT($\not{\pi}$), χEFT: 5 LEC constants, model independent
  - S. L. Zhu et al., Nucl. Phys. A748 (2005) 435
  - L. Girlanda, Phys. Rev. C77 (2008) 067001
  - D. R. Phillips, M. R. Schindler, and R. P. Springer, Nucl. Phys. A822 (2009) 1

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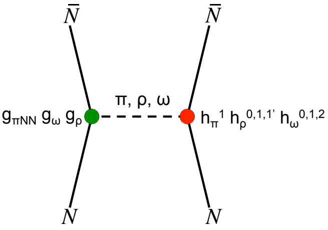
- $1/N_c$ expansions: $N_c \to$ large gives hierarchy of couplings
  - D. Phillips, D. Samart, and C. Schat, PRL 114 (2015) 062301
  - M. R. Schindler, R. P. Springer, and J. Vanasse, PRC 93 (2016) 025502
  - Gardner, Haxton, Holstein, ARNPS 67, 69 (2017)

Hadronic Weak interaction: DDH

- Low energy NN interaction in terms of the lowest energy mesons in which the pseudoscalar π meson and ρ and ω vector mesons couple a weak vertex to a strong vertex
- To relate to observables, need to calculate matrix elements. DDH used quark model, SU(6) symmetry, and non-leptonic hyperon decays to make estimates of the couplings

$$
\begin{aligned}
V^{PV}_{DDH}(\vec{r}) = {} & i\frac{h^1_\pi g_{\pi NN}}{\sqrt{2}}\left(\frac{\boldsymbol{\tau_1}\times\boldsymbol{\tau_2}}{2}\right)_z(\boldsymbol{\sigma_1}+\boldsymbol{\sigma_2})\cdot\left[\frac{\boldsymbol{p_1}-\boldsymbol{p_2}}{2m_N}, w_\pi(\boldsymbol{r})\right] \\
& - g_\rho\left(h^0_\rho\boldsymbol{\tau_1}\cdot\boldsymbol{\tau_2} + h^1_\rho\left(\frac{\boldsymbol{\tau_1}\times\boldsymbol{\tau_2}}{2}\right)_z + \frac{h^2_\rho}{2\sqrt{6}}\left((3\boldsymbol{\tau_1}\cdot\boldsymbol{\tau_2})_z - \boldsymbol{\tau_1}\cdot\boldsymbol{\tau_2}\right)\right) \\
& \times\left((\boldsymbol{\sigma_1}-\boldsymbol{\sigma_2})\cdot\left\{\frac{\boldsymbol{p_1}-\boldsymbol{p_2}}{2m_N}, w_\rho(\boldsymbol{r})\right\} + i(1+\chi_V)\boldsymbol{\sigma_1}\times\boldsymbol{\sigma_2}\cdot\left[\frac{\boldsymbol{p_1}-\boldsymbol{p_2}}{2m_N}, w_\rho(\boldsymbol{r})\right]\right) \\
& - g_\omega\left(h^0_\omega + h^1_\omega\left(\frac{\boldsymbol{\tau_1}\times\boldsymbol{\tau_2}}{2}\right)_z\right) \\
& \times\left((\boldsymbol{\sigma_1}-\boldsymbol{\sigma_2})\cdot\left\{\frac{\boldsymbol{p_1}-\boldsymbol{p_2}}{2m_N}, w_\omega(\boldsymbol{r})\right\} + i(1+\chi_S)\boldsymbol{\sigma_1}\times\boldsymbol{\sigma_2}\cdot\left[\frac{\boldsymbol{p_1}-\boldsymbol{p_2}}{2m_N}, w_\omega(\boldsymbol{r})\right]\right) \\
& + \left(\left(\frac{\boldsymbol{\tau_1}\times\boldsymbol{\tau_2}}{2}\right)_z(\boldsymbol{\sigma_1}+\boldsymbol{\sigma_2})\cdot\right)g_\rho h^1_\rho\left\{\frac{\boldsymbol{p_1}-\boldsymbol{p_2}}{2m_N}, w_\rho(\boldsymbol{r})\right\} - g_\omega h^1_\omega\left\{\frac{\boldsymbol{p_1}-\boldsymbol{p_2}}{2m_N}, w_\omega(\boldsymbol{r})\right\}\Bigg) \\
& - i g_\rho h^{1'}_\rho\left(\frac{\boldsymbol{\tau_1}\times\boldsymbol{\tau_2}}{2}\right)_z(\boldsymbol{\sigma_1}+\boldsymbol{\sigma_2})\cdot\left[\frac{\boldsymbol{p_1}-\boldsymbol{p_2}}{2m_N}, w_\rho(\boldsymbol{r})\right]
\end{aligned}
$$



B. Desplanques, J. F. Donoghue, and B. R. Holstein, Annals of Physics, vol. 124, no. 2, pp. 449 - 495, 1980

Hadronic Weak Interaction: DDH

- Attractive theory: can use experimental data and symmetry from the SM to try and predict couplings, calculate few and many body
- Benchmark for 20 years. Created “reasonable range" and “best values" (not fits or actual determinations!) Strong interactions dominate range; take them lightly (error $\sim$ 100%)

Coupling	DDH Reasonable Range	DDH Best Value	DZ	FCDH
h_π^1	0.0 $\longleftrightarrow$ 11.4	4.6	1.1	2.7
h_ρ^0	-30.8 $\longleftrightarrow$ 11.4	-11.4	-8.4	-3.8
h_ρ^1	-0.38 $\longleftrightarrow$ 0.0	-0.19	0.4	-0.4
h_ρ^2	-11.0 $\longleftrightarrow$ -7.6	-9.5	-6.8	-6.8
h_ω^0	-10.3 $\longleftrightarrow$ 5.7	-1.9	-3.8	-4.9
h_ω^1	-1.9 $\longleftrightarrow$ -0.8	-1.1	-2.3	-2.3

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h_ω^1	-1.9 $\longleftrightarrow$ -0.8	-1.1	-2.3	-2.3

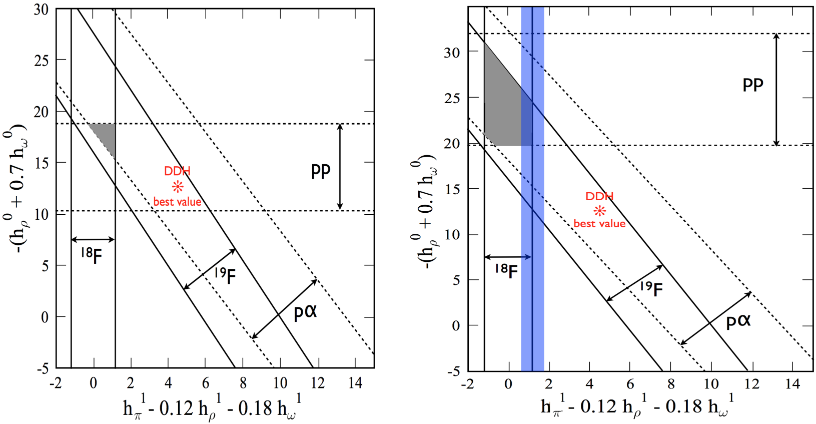
- Initially thought $\Delta I = 1$ could be large $\rightarrow$ motivated various experiments (including NPDGamma, $A_\gamma = -0.107 h_\pi^1$)

B. Desplanques, J. F. Donoghue, and B. R. Holstein, Annals of Physics, **124**, 2 (1980)

Extracting the Couplings from Observables in DDH?

Heavy Nuclei had a natural basis:

$$X_{N(n,p)} = 5.5(h^1_\pi \pm 0.12 h^1_\rho \pm 0.18 h^1_\omega) - 1.1(h^0_\rho + 0.7 h^0_\omega)$$



- 6→2 projection proved to be incompatible: too much theoretical error

W. C. Haxton and B. R. Holstein, Progress in Particle and Nuclear Physics, 2013

Hadronic Weak interaction: Pionless EFT

Pionless EFT (EFT($\not\pi$))

- Below pion production, can choose photons and nucleons (instead of gluons, which are in bound states) as the only dynamical degrees of freedom, non-relativistic

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$$\begin{aligned}\mathcal{L}_{PV} = -\Big[&\mathcal{C}^{(^3S_1-^1P_1)}\left(N^T\sigma^2\vec{\sigma}\tau^2N\right)^\dagger\cdot\left(N^T\sigma^2\tau^2i\overleftrightarrow{D}N\right)\\ &+\mathcal{C}^{(^1S_0-^3P_0)}_{(\Delta I=0)}\left(N^T\sigma^2\tau^2\vec{\tau}N\right)^\dagger\left(N^T\sigma^2\vec{\sigma}\cdot\tau^2\vec{\tau}i\overleftrightarrow{D}N\right)\\ &+\mathcal{C}^{(^1S_0-^3P_0)}_{(\Delta I=1)}\,\epsilon_{3ab}\left(N^T\sigma^2\tau^2\tau^aN\right)^\dagger\left(N^T\sigma^2\vec{\sigma}\cdot\tau^2\tau^b\overleftrightarrow{D}N\right)\\ &+\mathcal{C}^{(^1S_0-^3P_0)}_{(\Delta I=2)}\,\mathcal{I}_{ab}\left(N^T\sigma^2\tau^2\tau^aN\right)^\dagger\left(N^T\sigma^2\vec{\sigma}\cdot\tau^2\tau^bi\overleftrightarrow{D}N\right)\\ &+\mathcal{C}^{(^3S_1-^3P_1)}\,\epsilon_{ijk}\left(N^T\sigma^2\sigma^i\tau^2N\right)^\dagger\left(N^T\sigma^2\sigma^k\tau^2\tau^3\overleftrightarrow{D}^jN\right)\Big]+\text{H.c.}\,,\end{aligned}$$

- 5 LECs. Can only use two-body systems

M. Schindler, R. Springer, Progress in Particle and Nuclear Physics (2013)
M. Schindler, R. Springer, J. Vanasse, PRC (2016)

Hadronic Weak Interaction: $1/N_c$ hierarchy

- Basic principle: find LO, NLO, NNLO... in $1/N_c$ expansion
- Can estimate the couplings to 30%! Terms can come in as $\mathcal{O}(N_c)$ or $\mathcal{O}(1/N_c)$ along with factors of $\sin^2(\theta_W)$, which come along from the Lagrangian

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- First, Phillips et al used the $1/N_c$ expansion of QCD to tackle the PV NN force in the DDH framework

$$h_\rho^0 \sim \sqrt{N_c}, \qquad h_\rho^2 \sim \sqrt{N_c}$$
$$\frac{h_\rho^{1'}}{\sin^2\theta_W} \lesssim \sqrt{N_c}, \qquad \frac{h_\omega^1}{\sin^2\theta_W} \sim \sqrt{N_c}$$
$$\frac{h_\rho^1}{\sin^2\theta_W} \lesssim \frac{1}{\sqrt{N_c}}, \qquad \frac{h_\pi^1}{\sin^2\theta_W} \lesssim \frac{1}{\sqrt{N_c}}, \qquad h_\omega^0 \sim \frac{1}{\sqrt{N_c}}$$

D. Phillips, D. Samart, and C. Schat, PRL 114 (2015) 062301

Hadronic Weak Interaction: $1/N_c$ hierarchy EFT

- First developed by Schindler et al in EFT($\not\pi$) (5 couplings), with LEC $\mathcal{C}$'s (related to the DDH couplings and the Λ's in the following)
- Showed that the two isoscalar terms are related to one another by a factor of 3 up to $\mathcal{O}(1/N_c^2)$ corrections. Can go from 5 $\rightarrow$ 4 effective couplings

$$\begin{aligned}
\mathcal{C}^{(^3S_1-^1P_1)} &\sim N_c \ , \\
\mathcal{C}^{(^1S_0-^3P_0)}_{(\Delta I=0)} &\sim N_c \ , \\
\mathcal{C}^{(^1S_0-^3P_0)}_{(\Delta I=1)} &\sim N_c^0 \sin^2\theta_W \ , \\
\mathcal{C}^{(^1S_0-^3P_0)}_{(\Delta I=2)} &\sim N_c \ , \\
\mathcal{C}^{(^3S_1-^3P_1)} &\sim N_c^0 \sin^2\theta_W \ .
\end{aligned} \tag{33}$$

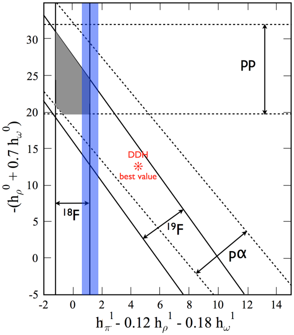
As before, the two isoscalar terms are not independent at leading order in the large-N_c counting, but up to $1/N_c^2$ corrections are related by

$$\mathcal{C}^{(^3S_1-^1P_1)} = 3\,\mathcal{C}^{(^1S_0-^3P_0)}_{(\Delta I=0)} \ . \tag{34}$$

M. R. Schindler, R. P. Springer, and J. Vanasse, PRC 93 (2016) 025502

Hadronic Weak Interaction: $1/N_c$ hierarchy EFT

- A recent review by Gardner, Haxton, and Holstein (GHH) finds a new basis of LO and makes predictions using a mapping from DDH



$\rightarrow$

$$
\begin{aligned}
V_{\mathrm{LO}}^{\mathrm{PNC}}(\boldsymbol{r}) = \Lambda_0^{^1S_0-^3P_0} & \left(\frac{1}{i}\frac{\overleftrightarrow{\nabla}_A}{2m_N}\frac{\delta^3(\boldsymbol{r})}{m_\rho^2}\cdot(\boldsymbol{\sigma}_1-\boldsymbol{\sigma}_2) - \frac{1}{i}\frac{\overleftrightarrow{\nabla}_S}{2m_N}\frac{\delta^3(\boldsymbol{r})}{m_\rho^2}\cdot i(\boldsymbol{\sigma}_1\times\boldsymbol{\sigma}_2)\right) \\
+ \Lambda_0^{^3S_1-^1P_1} & \left(\frac{1}{i}\frac{\overleftrightarrow{\nabla}_A}{2m_N}\frac{\delta^3(\boldsymbol{r})}{m_\rho^2}\cdot(\boldsymbol{\sigma}_1-\boldsymbol{\sigma}_2) + \frac{1}{i}\frac{\overleftrightarrow{\nabla}_S}{2m_N}\frac{\delta^3(\boldsymbol{r})}{m_\rho^2}\cdot i(\boldsymbol{\sigma}_1\times\boldsymbol{\sigma}_2)\right) \\
+ \Lambda_1^{^1S_0-^3P_0} & \left(\frac{1}{i}\frac{\overleftrightarrow{\nabla}_A}{2m_N}\frac{\delta^3(\boldsymbol{r})}{m_\rho^2}\cdot(\boldsymbol{\sigma}_1-\boldsymbol{\sigma}_2)(\tau_{1z}+\tau_{2z})\right) \\
+ \Lambda_1^{^3S_1-^3P_1} & \left(\frac{1}{i}\frac{\overleftrightarrow{\nabla}_A}{2m_N}\frac{\delta^3(\boldsymbol{r})}{m_\rho^2}\cdot(\boldsymbol{\sigma}_1+\boldsymbol{\sigma}_2)(\tau_{1z}-\tau_{2z})\right) \\
+ \Lambda_2^{^1S_0-^3P_0} & \left(\frac{1}{i}\frac{\overleftrightarrow{\nabla}_A}{2m_N}\frac{\delta^3(\boldsymbol{r})}{m_\rho^2}\cdot(\boldsymbol{\sigma}_1-\boldsymbol{\sigma}_2)(\boldsymbol{\tau}_1\otimes\boldsymbol{\tau}_2)_{20}\right),
\end{aligned}
$$

Coeff	DDH	Girlanda	Large N_c
$\Lambda_0^+ \equiv \frac{3}{4}\Lambda_0^{^3S_1-^1P_1} + \frac{1}{4}\Lambda_0^{^1S_0-^3P_0}$	$-g_\rho h_\rho^0(\frac{1}{2}+\frac{5}{2}\chi_\rho) - g_\omega h_\omega^0(\frac{1}{2}-\frac{1}{2}\chi_\omega)$	$2\mathcal{G}_1+\tilde{\mathcal{G}}_1$	$\sim N_c$
$\Lambda_0^- \equiv \frac{1}{4}\Lambda_0^{^3S_1-^1P_1} - \frac{3}{4}\Lambda_0^{^1S_0-^3P_0}$	$g_\omega h_\omega^0(\frac{3}{2}+\chi_\omega) + \frac{3}{2}g_\rho h_\rho^0$	$-\mathcal{G}_1-2\tilde{\mathcal{G}}_1$	$\sim 1/N_c$
$\Lambda_1^{^1S_0-^3P_0}$	$-g_\rho h_\rho^1(2+\chi_\rho) - g_\omega h_\omega^1(2+\chi_\omega)$	$\mathcal{G}_2$	$\sim \sin^2\theta_w$
$\Lambda_1^{^3S_1-^3P_1}$	$\frac{1}{\sqrt{2}}g_{\pi NN}h_\pi^1\left(\frac{m_\rho}{m_\pi}\right)^2 + g_\rho(h_\rho^1 - h_\rho^{1\prime}) - g_\omega h_\omega^1$	$2\mathcal{G}_6$	$\sim \sin^2\theta_w$
$\Lambda_2^{^1S_0-^3P_0}$	$-g_\rho h_\rho^2(2+\chi_\rho)$	$-2\sqrt{6}\mathcal{G}_5$	$\sim N_c$

Gardner, Haxton, Holstein, ARNPS 67, 69 (2017)

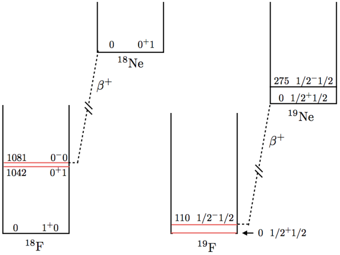
Hadronic Weak Interaction: Theory Outlook

- DDH is an important theoretical framework. It is model dependent, but can still be used to describe experiments
- Lots of theoretical work has been done and ongoing. $1/N_c$ hierarchy is a great step forward
- pionless EFT, 2-body, 4 (5-1) LECs = at least 4 experiments
  - $\vec{n} + p \to d + \gamma$ spin-angular asymmetry (completed, $\sim$47% error)
  - $\vec{n} + p \to d + \gamma$ circular polarization (large error)
  - $n - p$ spin rotation
  - $p - p$ longitudinal asymmetry (completed, $\sim$16% error)
  - $\vec{\gamma} + d \to n + p$ (difficult, not bright enough γ source)
- EFT, GHH, DDH equivalent
  - Few- and many-body calculations ongoing
  - Difficult theory, but can express observables in the theory
- LQCD has a calculation of $\Delta I = 2$ on the radar

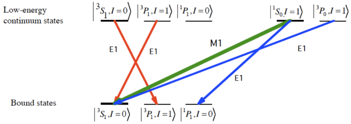
Hadronic Weak Interaction: Experiments

Experimental approaches:

- Heavy Nuclei:
  - Small level spacings $\rightarrow$ large PV signals
  - Theoretical interpretations more difficult

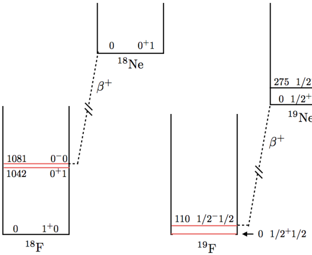


- Few-body:
  - Large level spacings $\rightarrow$ small PV signals
  - Little or no theoretical error



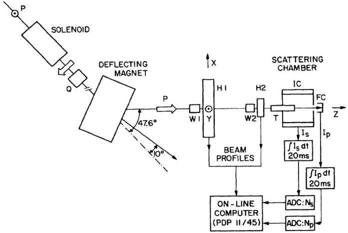
Hadronic Weak interaction: Heavy Nuclei Experiments

- ^{18}F: $P_\gamma = 12 \pm 38 \times 10^{-5}$ (Caltech/Seattle, Mainz, Florence, Queens)
  - Mixing of the 0^+, $\Delta I = 1$ decay into the 0^-, $\Delta I = 0$ state gives circular polarization in the 1.081 MeV γ emitted: $\rightarrow =$ pure $\Delta I = 1$ transition
  - Small mass difference between the two states acts as a nuclear amplifier
  - Couplings: $4385 h^1_\pi - 492 h^1_\rho - 833 h^1_\omega$
- ^{19}F: $A_\gamma = 7.4 \pm 1.9 \times 10^{-5}$ (Seattle, Mainz)
  - Angular asymmetry in the polarized excited $1/2^-$ to the $1/2^+$ ground state
  - Couplings: -94.2h^1_π - 10.2h^1_ρ - 16.9h^1_ω +34.1h^0_ρ + 19.4h^0_ω



Gardner, Haxton, Holstein, ARNPS 67, 69 (2017)

Hadronic Weak interaction: $\not{P}$ Few-body Experiments



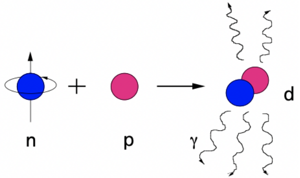
$\vec{p} - \vec{p}$ scattering: best constraints still

- A_L = -0.93 $\pm$ 0.21 (13 MeV, Bonn), -1.7 $\pm$ 0.8 (15 MeV, LANL), -1.57 $\pm$ 0.23 $\times 10^{-7}$ (45 MeV, PSI)
  - Longitudinal analyzing power of polarized protons on an un-polarized target
  - DDH: $-(h_\rho^0 - 0.7h_\omega^0)$ = 25 $\pm$ 6.1

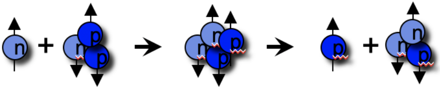
$\vec{p} - \vec{\alpha}$ scattering

- A_L = 3.3 $\pm$ 0.9 $\times 10^{-7}$ (46 MeV, PSI)
  - Longitudinal analyzing power of protons on ^{4}He target
  - DDH: -0.34h_π^1 - 0.05h_ρ^1 - 0.06h_ω^1 + 0.14h_ρ^0 + 0.06h_ω^0 = 3.3 $\pm$ 0.9
  - Similar combination as ^{19}F

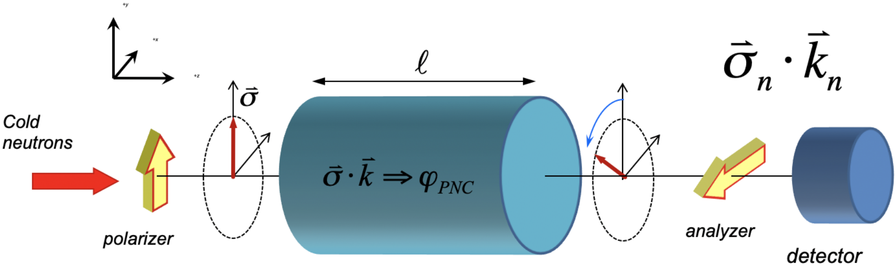
NPDGamma, n-3He, and Neutron Spin Rotation in 4He



$$\vec{\sigma}_n \cdot \vec{k}_\gamma$$

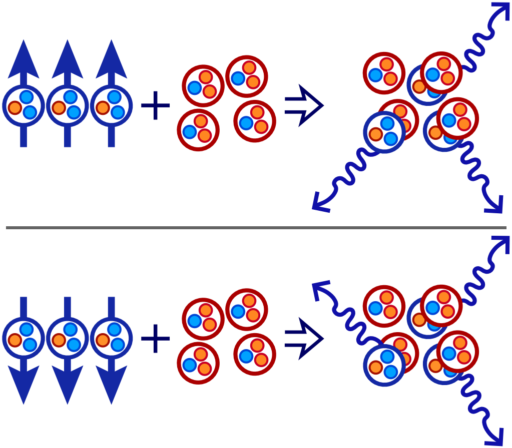


$$\vec{\sigma}_n \cdot \vec{k}_p$$



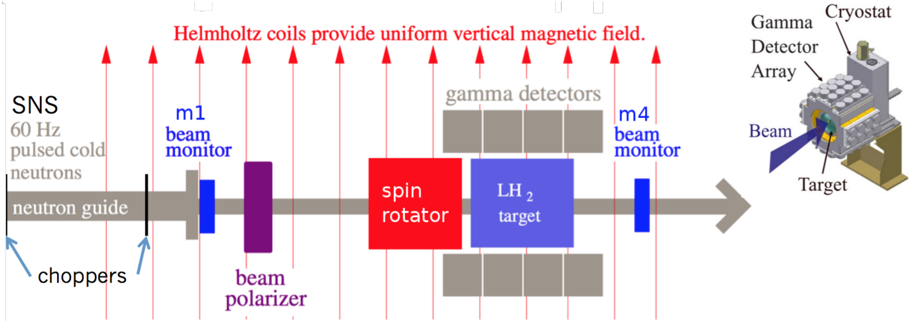
Hadronic Weak interaction: NPDGamma

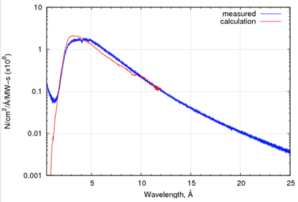
NPDGamma ($\vec{\sigma} \cdot \vec{k}$) at the SNS at ORNL, goal: $h_\pi^1 \sim 1 \times 10^{-7}$



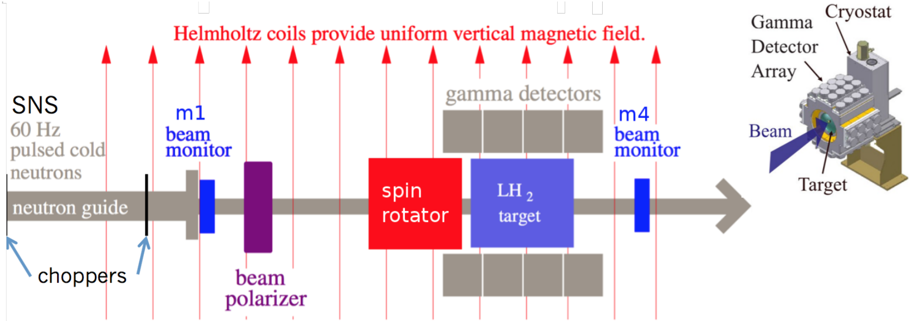
- Flipping the neutron polarization is equivalent to a parity transformation
- Large statistics! Must collect 10^{16} photons to see 10^{-8} asymmetry!

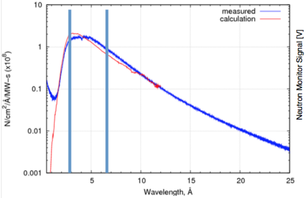
NPDGamma Apparatus Layout

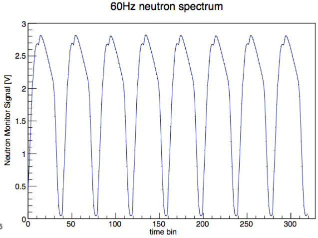




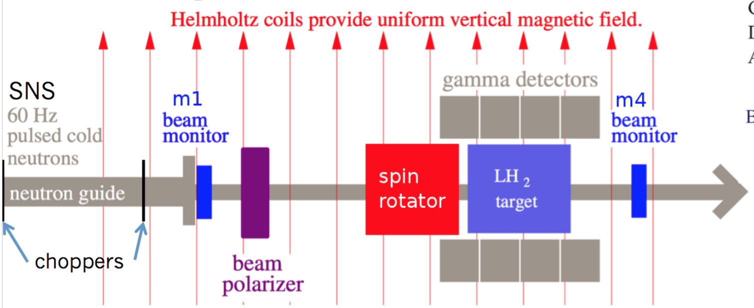
NPDGamma Apparatus Layout

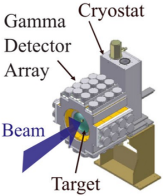


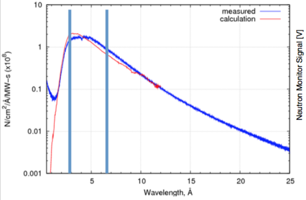


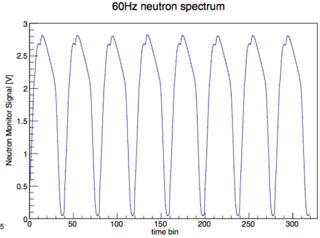


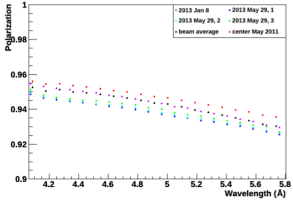
NPDGamma Apparatus Layout



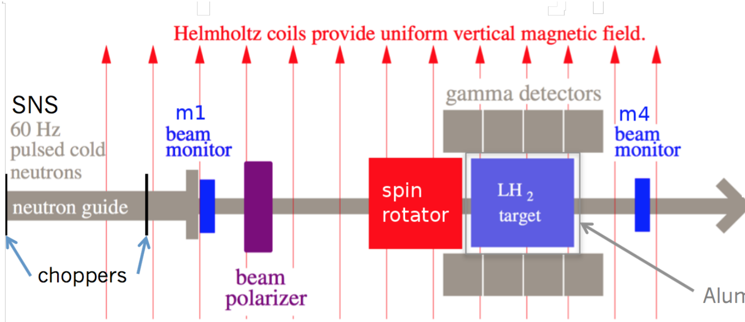


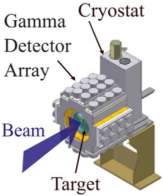


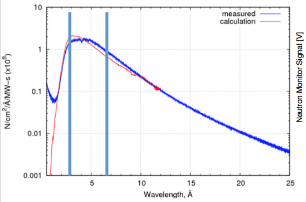


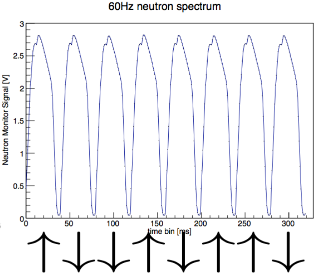


NPDGamma Apparatus Layout



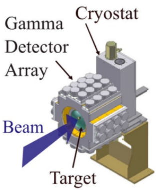


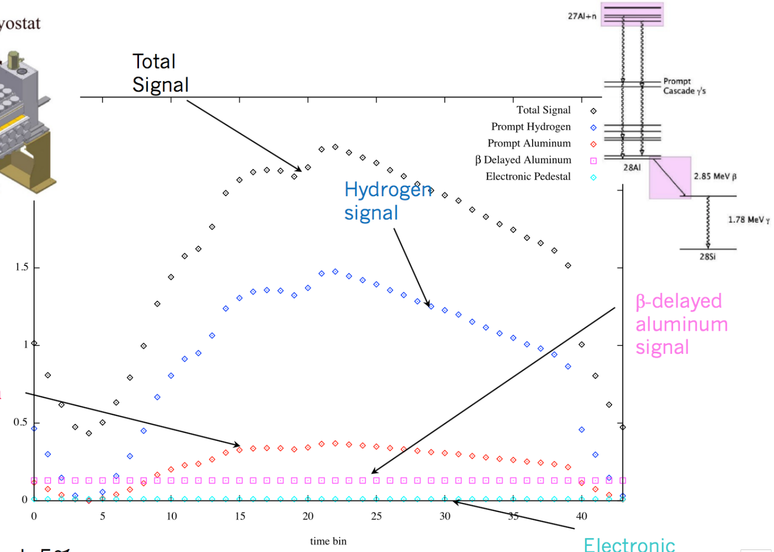




- Resonant Spin Rotator flips spins each pulse to cancel time dependent detector gain drifts
- Neutrons capture in LH_2 target, detected in a 3π CsI detector array (48)

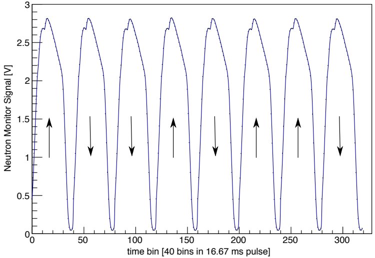
NPDGamma Fractions of the Signal



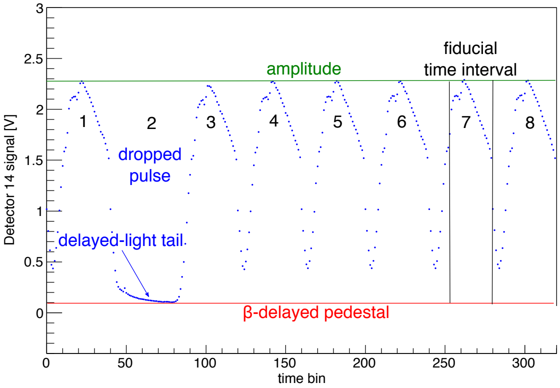


H: 80%
Al: 20%
β -delayed: 5%

NPDGamma Asymmetry Normalization

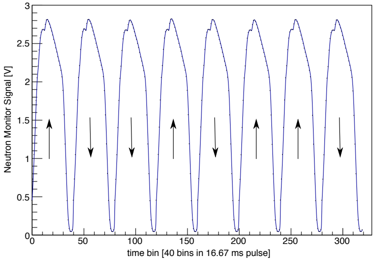


$$A_{raw} = \frac{N^{\uparrow} - N^{\downarrow}}{N^{\uparrow} + N^{\downarrow}}$$

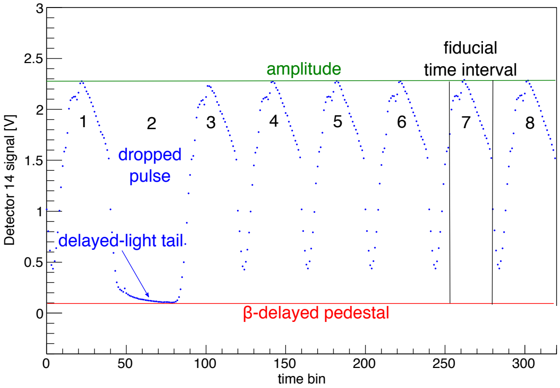


- In order to normalize the asymmetry and eliminate the constant β-delayed aluminum and the delayed-light, multi-component phosphorescence tail ($\sim$7 ms), we used regularly dropped pulses

NPDGamma Asymmetry Normalization



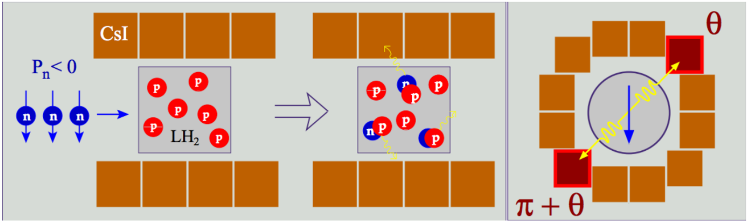
$$A_{raw} = \frac{N^{\uparrow} - N^{\downarrow}}{N^{\uparrow} + N^{\downarrow}}$$



- dropped pulses contain all non-prompt contributions. Independent analyses use a template fit to pulses or more advanced normalization sum ($A_d = \dfrac{\sum_{\uparrow} X_d^{\uparrow} - \sum_{\downarrow} X_d^{\downarrow}}{N * \left| \sum_{i=0}^{M-1} [2 * (i \bmod 2) - 1] * X_{d,i} \right|}$) to properly normalize the asymmetry

NPDGamma Physics Asymmetry Extraction

$$A_{raw} = P_{tot}\left(A_{UD}cos\theta + A_{LR}sin\theta\right)$$ Ideal!



$$A_i^{raw} = P_{tot}^H f_i^H \left(G_{UD,i}^H A_{UD}^H + G_{LR,i}^H A_{LR}^H\right) + P_{tot}^{Al} f_i^{Al}\left(G_{UD,i}^{Al} A_{UD}^{Al} + G_{LR,i}^{Al} A_{LR}^{Al}\right)$$

Apply polarization, spin flip efficiency, depolarization corrections (P_{tot}), subtract Aluminum UD and LR asymmetries with appropriate fractions. Al fraction is on average 20%.

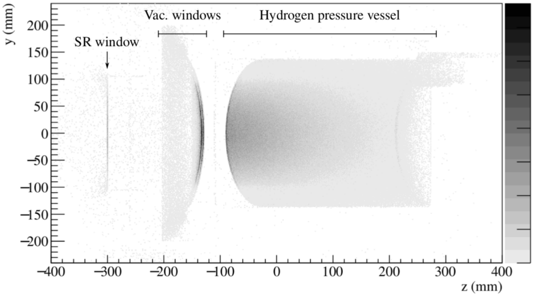
Have to **measure** PV Aluminum asymmetry and **calculate** geometry factors!

The Saga of the Aluminum Asymmetry

- We measured the Al asymmetry in 2014 $\rightarrow$ PV contaminations!
- Re-measured in 2016 after n-3He

The Saga of the Aluminum Asymmetry

- We measured the Al asymmetry in 2014 $\rightarrow$ PV contaminations!
- Re-measured in 2016 after n-3He
- 2016: Assumed each aluminum was not the same and determined proper ratio of actual LH target components to make a *composite target* **using a detailed Geant4 simulation**.



Courtesy David Blyth

Simultaneous Asymmetry Extraction

- Usually when you have a measurement that contains two asymmetries from two different sources, they are 'subtracted'
- For NPDGamma, we simultaneously extract the hydrogen and aluminum asymmetries through our 'Grand χ^2'

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- For NPDGamma, we simultaneously extract the hydrogen and aluminum asymmetries through our 'Grand χ^2'

$$\chi^2_{grand} = \sum_i \frac{\left[A_i^{raw,H} - \left(G'^{H}_{UD,i} A^H_{UD} + G'^{H}_{LR,i} A^H_{LR} + \sum_j \left(G'^{Al,H,j}_{UD,i} A^{Al,j}_{UD} + G'^{Al,H,j}_{LR,i} A^{Al,j}_{LR}\right)\right)\right]^2}{\sigma^2_{A_i^{raw,H}}}$$

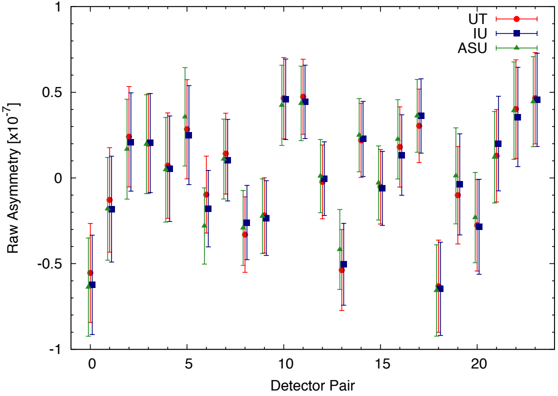
$$+ \sum_i \frac{\left[A_i^{raw,Al} - \sum_j \left(G'^{Al,Al,j}_{UD,i} A^{Al,j}_{UD} + G'^{Al,Al,j}_{LR,i} A^{Al,j}_{LR}\right)\right]^2}{\sigma^2_{A_i^{raw,Al,j}}}$$

$j =$ types of aluminum.

with primed geometry factors as $G'^{Z}_{UD,i} \equiv P_{tot} f_i^Z G^Z_{UD,i}$ and $G'^{Z}_{LR,i} \equiv P_{tot} f_i^Z G^Z_{LR,i}$

The hydrogen asymmetry measurement influences the aluminum!

NPDGamma Final Results



- Three separate analyses agreed at the few 10^{-10} level!

$$\boxed{A_\gamma = -3.0 \pm 1.4 \times 10^{-8}}$$

- h_π^1 = (2.6 ± 1.2) $\times 10^{-7}$, $C^{3_1^S \to {}^3P_1} / C_0 = -7.4 \pm 3.5 \times 10^{-11}$ MeV^{-1}, $\Lambda_1^{{}^3S_1 - {}^3P_1}$ = 810 ± 380 $\times 10^{-7}$, **see D. Bowman's talk on implications**

NPDGamma Collaboration

NPDGamma proposal: 1999 – 20 year anniversary!

27 Institutions

Arizona (1), Bhabha Atomic Research Centre (2), U California/Davis (3), Dayton (4), Dubna (5), Hamilton (6), U Indiana (7), Jlab (8), KEK (9), U Kentucky (10), Lanzhou U (11), Los Alamos (12), U Manitoba (13), Michigan/Ann Arbor (14), U Nevada (15), U New Hampshire (16), NIST (17), U California/Berkeley(18), ORNL (19), PSI (20), Shanghai Institute of Applied Physics (21), U Tennessee Knoxville (22), U Tennessee Chattanooga (23), Universidad Nacional Autonoma de Mexico (24), TRIUMF (25), U Virginia (26), Western Kentucky U (27)

- 93 Individuals and 15 PhD's

Ricardo Alarcon (1), Septimiu Balascuta (1), David Blyth (1), Satyaranjan Santra (2), Greg Mitchell (3), Todd Smith (4), Eduard Sharapov (5), Gordon Jones (6), Mike Snow (7), Hermann Nann (7), Changbo Fu (7), Chad Gillis (7), Zhaowen Tang (7), Walt Fox (7), John Vanderwerp (7), Jiawei Mei (7), Jason Fry (7), Mark Leuschner(7), Roger Carlini (8), Silviu Covrig (8), Yasuhiro Masuda (9), Y. Matsuda (9), Akira Masaike (9), Takahasu Ino (9), S. Muto (9), S. Ishimoto (9), Chris Crawford (10), Elise Tang (10), Kayla Craycraft (10), William Berry (10), Latiful Kabir (10), Yanbin Zhang (11), Scott Wilburn (12), Vinny Yuan (12), D. Smith (12), S. Lamoreaux (12), James Knudson (12), Nadia Fomin (12), Vincent Yuan (12), Mike Gericke (13), Shelley Page (13), Rob Mahurin (13), Mark McCrea (13), Tim Chupp (14), M. Sharma (14), K. Coulter (14), Todd Smith (14), Alex Barzilov (15), John Calarco (16), Bill Hersman (16), Michael Dabaghyan (16), Tom Gentile (17), Gordon Jones (17), S. Freedman (18), B. Fujikawa (18), David Bowman (19), Seppo Penttila (19), Paul Mueller (19), Erick Iverson (19,22), Tony Tong (19), Rick Allen (19), Jack Thomison (19), Chris Blessinger (19), Bernard Lauss (20), Wang Xu (21), Yongjiang Li (21), Geoff Greene (19,22), Serpil Kucuker (22), Matt Musgrave (22), Kyle Grammer (22), Chris Hayes (22), Noah Birge (22), Chris Coppola (22), Josh Hamblen (23), Daniel Parsons (23), Jeremy Stuart (23), Seth Waldecker (23), Libertad Barron-Palos (24), Jose Favela (24), Curiel Garcia (24), Marissa Maldonado-Velazquez (24), Paul Delheij (25), W.D. Ramsay (25), Stefan Baeßler (26), Dinko Pocanic (26), Emil Frlez (26), Americo Salas-Bacci (26), Loreto Pete Alonzi (26), Maxim Bychkov (26), Evan Askanazi (26), Pil-Neyo Seo (26), Dylan Evans (26), Igor Novikov (27)

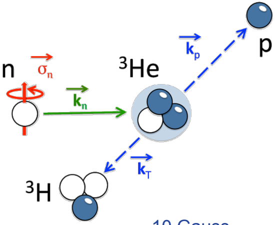
Hadronic Weak interaction: n-3He

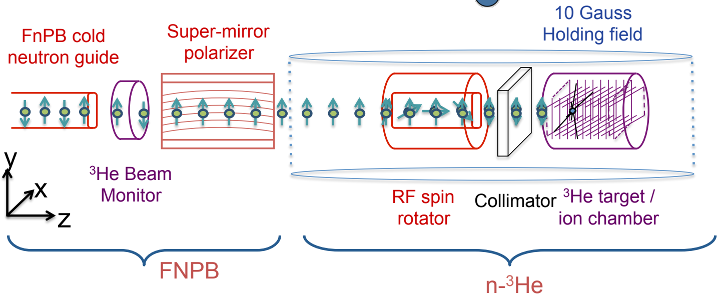
n-3He at the SNS at ORNL: $-0.19h^1_\pi - 0.05h^0_\omega - 0.02(h^1_\omega - h^1_\rho) - 0.04h^0_\rho - 0.001h^2_\rho$

Same beam monitor, SMP, holding field as NPDGamma

$$\sigma_\pm = \sigma_0\left(1 \pm A_{PC}\, \hat{\boldsymbol{k}}_n \times \hat{\boldsymbol{\sigma}}_n \cdot \hat{\boldsymbol{k}}_p \pm A_{PV}\, \underbrace{\hat{\boldsymbol{\sigma}}_n \cdot \hat{\boldsymbol{k}}_p}_{G_{\substack{\mathrm{LR}\\\mathrm{UD}}}}\right)$$

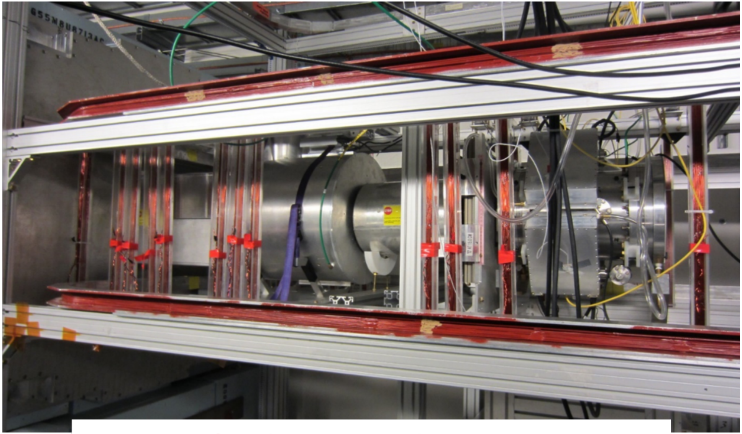
$$P_n A_{\substack{\mathrm{PC}\\\mathrm{PV}}} G_{\substack{\mathrm{LR}\\\mathrm{UD}}} = \frac{Y_+ - Y_-}{Y_+ + Y_-}$$

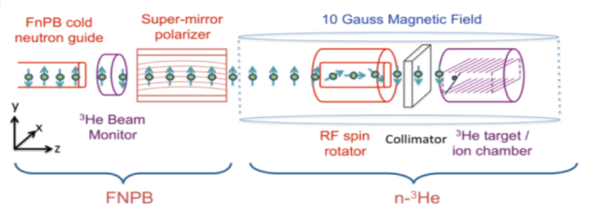




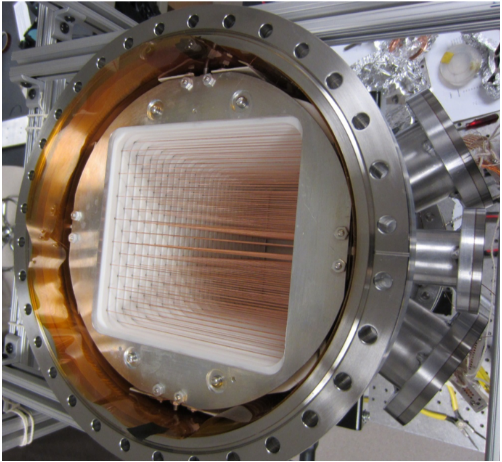
n-3He slides Courtesy Chris Crawford and Michael Gericke

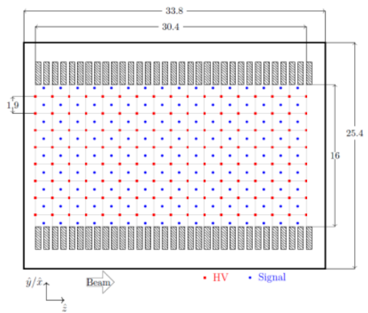
n-3He Apparatus

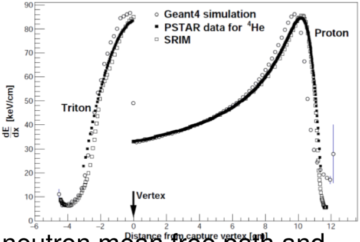




n-3He Target/Detector Chamber



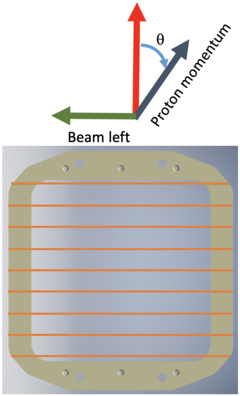


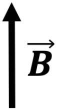


- Target/chamber filled with ^{3}He
- Optimize neutron wavelength range through neutron mean free path and proton range

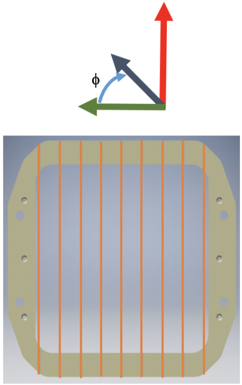
n-3He PV and PC Operation

Exploit symmetry and run in two orientations to measure PV and PC asymmetries.
Under perfect alignment conditions we could make independent measurements:





Rotate chamber around beam axis (beam into page)



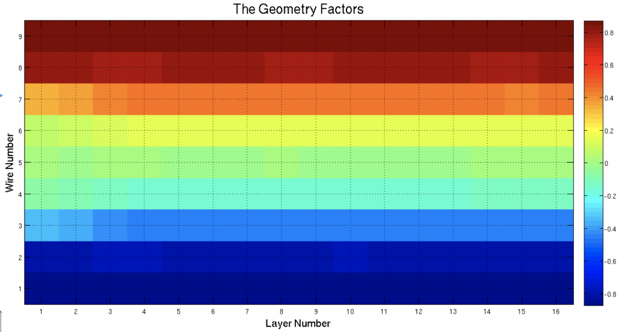
$$A_{meas} = f_{\exp}\left(A_{PV}\cos\theta_{\vec{s}_n\cdot\vec{k}_p} + \cancel{A_{PC}\cos\phi_{\vec{s}_n\times\vec{k}_n\cdot\vec{k}_p}}\right)$$

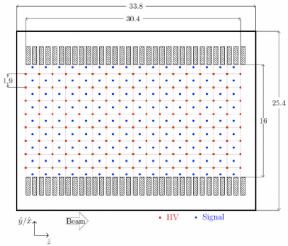
$$A_{meas} = f_{\exp}\left(\cancel{A_{PV}\cos\theta_{\vec{s}_n\cdot\vec{k}_p}} + A_{PC}\cos\phi_{\vec{s}_n\times\vec{k}_n\cdot\vec{k}_p}\right)$$

n-3He Geometry Factors

Finite geometry correction factors:

Conjugate wire pair rows

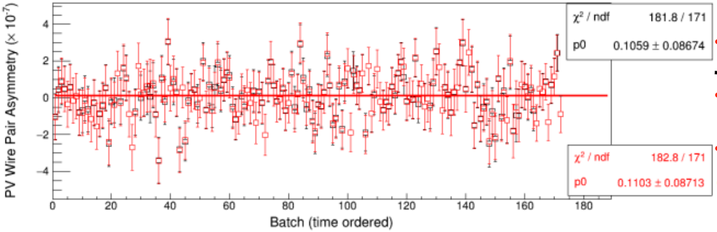


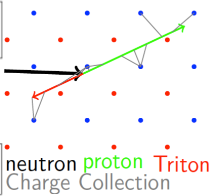


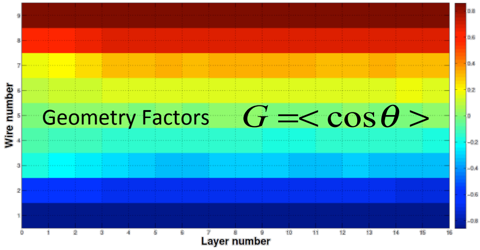
$$A_{meas} = f_{exp}\left(A_{PV}\cos\theta_{\vec{s}_n\cdot\vec{k}_p} + A_{PC}\cos\phi_{\vec{s}_n\times\vec{k}_n\cdot\vec{k}_p}\right)$$

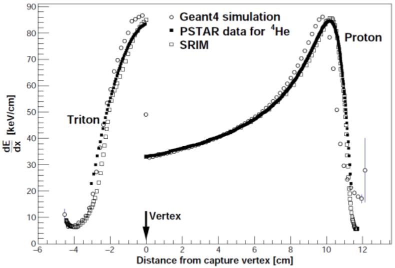
$$\Rightarrow A_{meas} = f_{exp}\left(A_{PV}G_{UD} + A_{PC}G_{LR}\right)$$

n-3He Results









$$\boxed{A_{PV} = 15.3 \pm 9.7(stat) \pm 2.5(sys)ppb}$$

PRL to be submitted, PRC planned

n-3He Collaboration

Spokespersons
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Project Manager
S. Penttila (ORNL)

S. Baessler (UVA), L. Barrón (UNAM),

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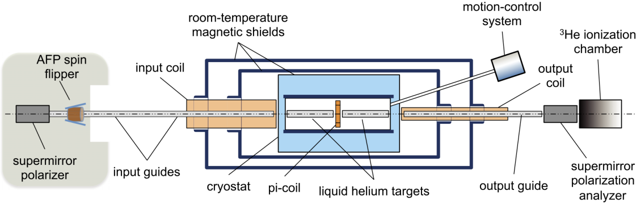
G. Greene (ORNL), J. Hamblen (U. Tennessee Chattanooga),

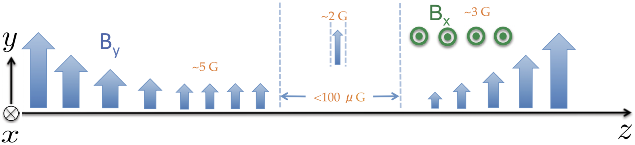
C. Hayes (U. Tennessee), K. Latiful (U Kentucky), M. McCrea (U. Manitoba),

A.R. Morales (UNAM), P. Mueller (ORNL), I. Novikov (Western Kentucky), C. Wickersham (U. Tennessee Chattanooga)

Hadronic Weak interaction: n-4He Spin Rotation

NSR in ^{4}He planned at NIST: $\frac{d\phi}{dz} = -0.97h^1_\pi - 0.22h^0_\omega + 0.22h^1_\omega - 0.32h^0_\rho + 0.11h^1_\rho$





- Previous result statistics limited: $+2.1 \pm 8.3$ (stat) $^{+2.9}_{-0.2}$ (sys) $\times 10^{-7}$ rad/m
- $\vec{\sigma} \cdot \vec{k}$ interaction causes an accumulation of phase: corkscrew motion!
- Use various configurations of magnetic fields to isolate the effect
- 5th force program at LANL using same apparatus (sans ^{4}He) finished, published in PRB https://doi.org/10.1016/j.physletb.2018.06.066

NSR in 4He

➢ Forward transmission of cold neutrons can be described using neutron optics with index of refraction *n*

$$n = 1 + \left(\frac{2\pi}{k^2}\right)\rho f(0)$$

➢ Express forward scattering amplitude in terms of parity-conserving (PC) and parity-violating (PNC) parts

$$f(0) = f_{PC} + f_{PNC}(\vec{\sigma}\cdot\vec{k})$$

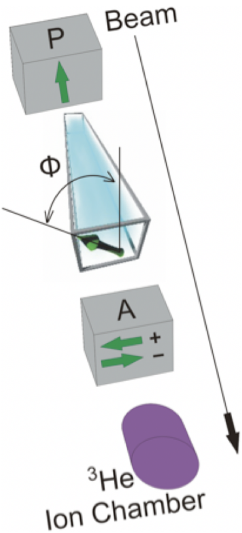
➢ As the neutron propagates along z, it accumulates a phase

$$\phi = kz\left[1 + \frac{2\pi\rho}{k^2}\left(f_{PC} + f_{PNC}(\vec{\sigma}\cdot\vec{k})\right)\right]$$

➢ For a transversely polarized beam, the phases of the two helicity states are different

$$\phi_{\pm} = \phi_{PC} \pm \phi_{PNC} \qquad \phi_{PNC} = 2\pi\rho z f_{PNC}$$

NSR in 4He



We need an angle measurement of O(10^{-7}) rad.

Target is placed between a crossed polarizer-analyzer pair (analyzing power *PA*).

PA sign is flipped every second, neutrons are detected in a ^{3}He ion chamber operated in current mode

$$\boxed{sin\phi = \frac{1}{PA}\frac{N_+ - N_-}{N_+ + N_-}}$$

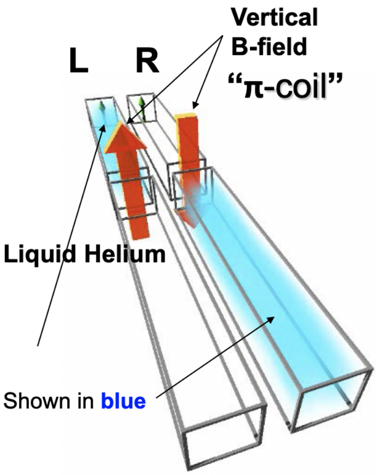
Two critical issues:

Beam intensity fluctuations threaten statistical error.

Hard to shield B below 10 μG with big holes. Rotation angle from this field is about 3 orders of magnetic greater than ϕ_{PNC} error.

What to do? Split the beam and oscillate the liquid

Isolating the PV signal



The left and right chambers are each divided in two as shown

2 target positions separated by vertical solenoid ("pi-coil")

- pi-coil tuned to precess neutrons about vertical field by 180° for the average neutron energy in the beam

PV Spin Angle
changes sign for
target position due to pi-coil

PC Spin Angle
is B-field dependent for each target
but is cancelled out due to the
left/right chambers

NSR in 4He

Statistical Improvement

➢ Counting statistics → Expect x40 more polarized neutron flux through apparatus from
1) NIST NCNR expansion and NG-C
2) Increasing apparatus acceptance

➢ Low duty factor → 1) Reduce heat load
2) Reduce fill/drain times
should give another factor of 4 in stats

Systematic Improvement

➢ Reduce B field in target region → 1) Goal of 10 μG using additional passive shielding and active trimming.

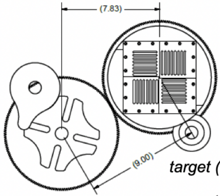
➢ Improve PA → 1) New supermirror polarizers with better reflectivity characteristics.
2) Characterize east-west beams
3) More frequent *PA* measurements

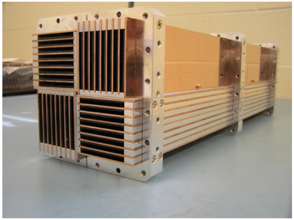
NSR in 4He

Spin-1 Boson Neutron Axial Coupling Search at LANSCE

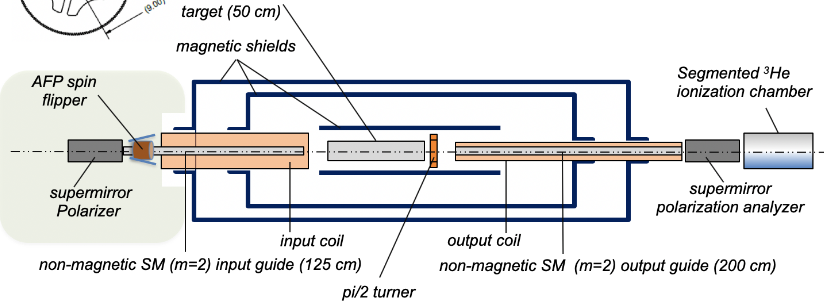
Geneva Mechanism:

Rotate the target by increments of 90°

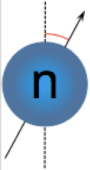




Plates of different nucleon density N are assembled so that the polarized neutrons traveling between the gaps will always see a nucleon density gradient.



NSR-3 collaboration:



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NSR Outlook

- New calculation shows that the pion contribution is much lower, dϕ/dz is dominated by $\Delta I = 0$ and sensitive to leading order terms in EFT $1/N_c$, and the predicted spin rotation is 4-12 $\times 10^{-7}$, depending on DDH best or $1/N_c$.
- Motivation for $n - p$ spin rotation:
  - Sensitive to leading order ΔI = 0,2
  - One of the 4 experiments needed for pionless EFT
  - Could have a large signal (expectation based on experimental data now)
  - Can use same components as for the helium spin rotation apparatus except for the cryogenic target

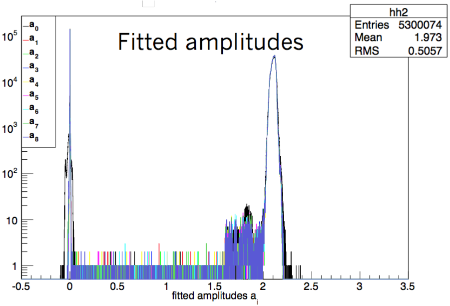
Summary and Outlook

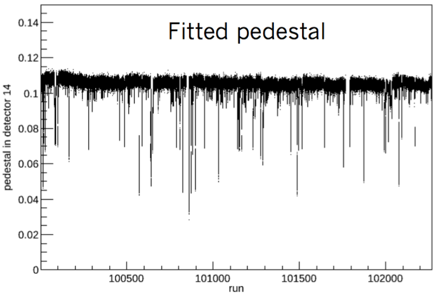
- Now have 3 few-body experiments (NPDGamma, n—^{3}He, and $p-p$)
- **David Bowman**: How to interpret HWI data
- **Chris Crawford**: What neutron experiments can we do going forward?
  - $\vec{n}-p$ spin rotation (ΔI = 0,2)
  - $n+p\rightarrow d+\gamma$ spin-angular (ΔI = 1) and circular polarization (ΔI = 0)
  - $\vec{n}+d\rightarrow t+\gamma$ (ΔI = 0,1)
  - $\vec{n}+^3\text{He}\rightarrow^3\text{H}+p$ (ΔI = 0,1)
  - $\vec{n}$—^{4}He spin rotation experiment is planned at NIST (ΔI = 0,1)
  - LQCD calculations of $\Delta I=2$!

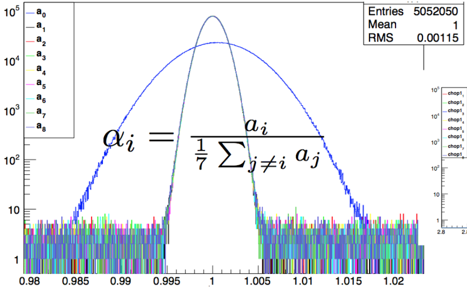
Completed, could be done with more precision
Done, current experimental limit does not contribute to the determination of the couplings
Not attempted

Extras

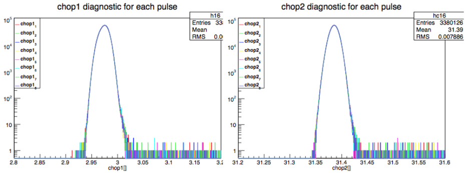
NPDGamma Diagnostics and Cuts





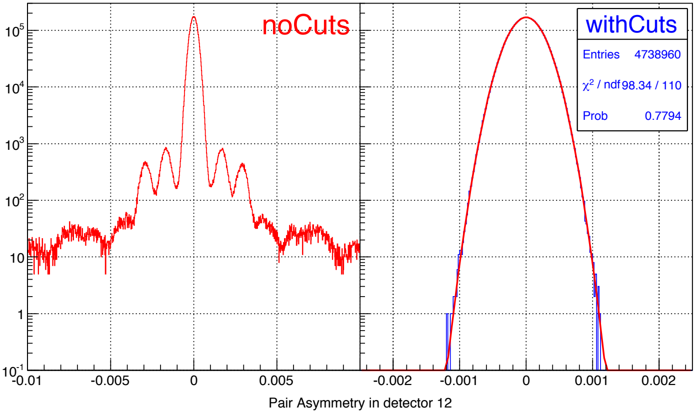


Chopper phase diagnostics



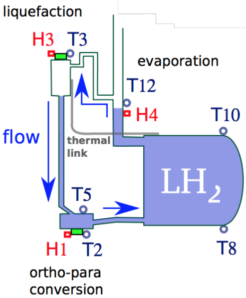
NPDGamma Pair Asymmetries - Before and After Cuts

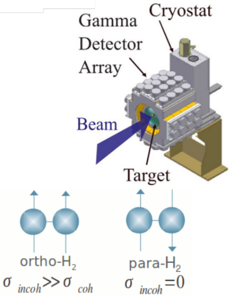
Pair asymmetries formed from normalized opposite pairs of detectors, 90° around the ring

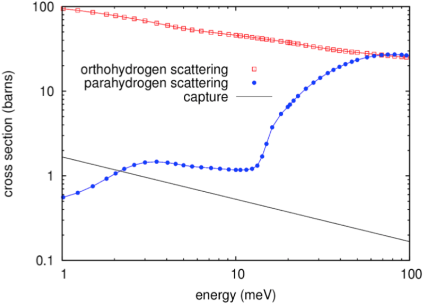


- $\sim$20% of data is eliminated, varying cuts does not affect the asymmetry
- Cuts are independent of polarization – very robust!

LH_2 Target

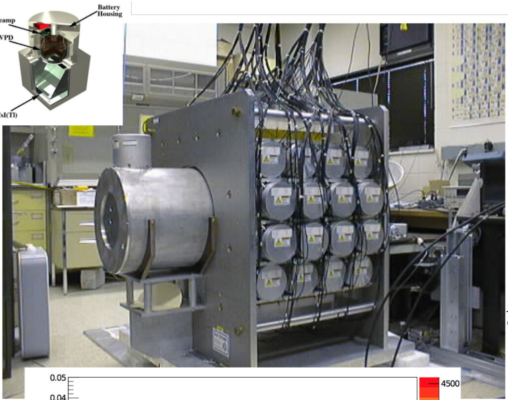


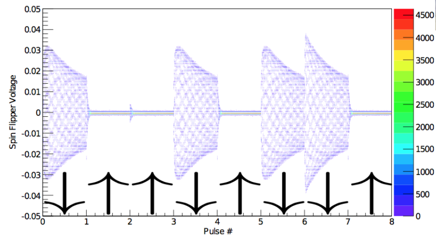




- Ortho significantly scatters and depolarizes a cold neutron beam
- Ortho thermodynamic equilibrium is low for liquid H temperatures
- Active circulation and catalyst to promote circulation from ortho to para
- Spin1 Ortho → Δ 15meV → Spin 0 para

SF and Detector Array





γ -Detector Array

- 4 rings of 12 CsI detectors → 48 total, form into 24 pairs
- 3π acceptance, current mode
- Rate: 100MHz

$$\frac{d\sigma}{d\Omega} \propto \frac{1}{4\pi}\left(1 + A_{UD}cos\theta + A_{LR}sin\theta\right)$$